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Einstein Observatory evidence for the widespread baryon overdensity in clusters of galaxies

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ABSTRACT

We analyse the X-ray surface brightness profiles of 19 moderately distant and luminous clusters of galaxies observed with the *Einstein Observatory* . Our aim is to determine cluster gas masses out to radii between 1 and 3 Mpc, and to confirm the apparent conflict, if $\Omega_0 = 1$, between the current calculations of the mean baryon fraction of the Universe expected from standard primordial nucleosynthesis, and the fraction of the mass in clusters which is in gas. Our analysis shows that baryon overdensities in clusters are much more widespread than only the Coma cluster with which S. White & Frenk originally highlighted this problem. The uncertainties involved in our analysis and some cosmological implications from our results are briefly discussed. For a refined sample of 13 clusters we find that the baryon fraction for the gas within 1 Mpc lies between 10 and 22 per cent.

Key words: galaxies: fundamental parameters, intergalactic medium, observations – cosmology: dark matter – X-rays: galaxies.

1 INTRODUCTION

Current constraints, from a comparison of standard, homogeneous, primordial nucleosynthesis calculations with light-element abundances by Walker et al. (1991, see also Olive et al. 1990 and Peebles et al. 1991), place tight limits on the baryon density parameter of the Universe, $\Omega_\mathrm{b} = 0.05 \pm 0.01 h_{50}^{-2}$ ($H_0 = 50 h_{50}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). This implies a mean baryon density of about < 6 per cent of the critical closure density if $h_{50} = 1$, which is much lower than the previous upper limit of $\Omega_\mathrm{b} < 0.19 h_{50}^{-2}$ determined by Yang et al. (1984). As first pointed out by S. White & Frenk (1991), the recent calculation of the mean baryon fraction conflicts with the X-ray determinations of the gas fraction of mass in clusters if $\Omega_0 = 1$. This fraction should equal $\Omega_\mathrm{b}/\Omega_0$ if dark matter is distributed similarly to the X-ray emitting gas. They, and more recently S. White et al. (1993), noted that hot gas contributes approximately 20 per cent to the total mass of the Coma cluster within approximately 3 Mpc, indicating that $\Omega_\mathrm{b}/\Omega_0 \sim 0.3$. Baryon fraction estimates for the Coma cluster have been extended to 5 Mpc, utilizing the 'unlimited' field of view of the *ROSAT* All-Sky Survey (Briel, Henry, & Böhringer 1992), where the gas mass content is then 30 per cent. Thus at face value, either $\Omega_0 \sim 0.2$, dark matter and baryons have different distributions on cluster scales, or the abundance measurements and/or calculations of Ω_b are incorrect. This last possibility is unlikely since it involves the best-understood physics.

Over a decade ago, Ku et al. (1983) determined that the baryon fraction within 1.9 Mpc of CA0340 − 538 was greater than 10 per cent, while Stewart et al. (1984) found variations between 3 and 20 per cent within the central 0.5 Mpc of 36 clusters, and that a significant number of clusters have baryon fractions of at least 10 per cent. Stewart et al. also noted that the baryon fraction increase with radius, a result supported by the analysis of *Einstein Observatory* data by Forman & Jones (1984) which showed that the scale-height of the gas distribution in clusters is generally larger than that of the gravitational mass. Edge & Stewart (1991b) also determined baryon fractions of up to 20 per cent from *EXOSAT* observations of 36 clusters of galaxies. However, none of these studies noted any conflict between the X-ray determinations of the baryon fraction and the constraints from standard primordial nucleosynthesis; the calculated limit of the baryon fraction at that time was $\Omega_\mathrm{b} < 0.19 h_{50}^{-2}$.

A recent study of the Shapley supercluster by Fabian (1991), where gas mass and luminosity relations from Forman & Jones (1984) are extrapolated, indicates that the baryon fraction there is greater than 18 per cent over a re-

gion of 37 Mpc in radius. This over-density of a factor of 3 implies that the baryons must have been accumulated from a region that is at least 40 per cent larger in radius, if $\Omega_0 = 1$. This then implies that the Shapley region must be bound, or has at least retarded the Hubble flow over this region, and creates problems for the theory of the formation of large-scale structure in currently favoured models.

If baryon over-densities are common in clusters, as we aim to show in this paper, then perhaps the most obvious solution is that $\Omega_0 < 1$ (*e.g.* for baryon fractions of 30 per cent $\Omega_b/\Omega_0 \lesssim 0.06/0.2 = 0.3$ — see also S. White & Frenk 1991, and S.White et al. 1993). However, this solution disagrees with the strong evidence for $\Omega_0 = 1$ from cluster evolution and substructure studies (Richstone, Loeb & Turner 1992), and the estimates obtained from the POTENT analysis of *IRAS* galaxy density fields and peculiar velocities (Nusser & Dekel 1993, Dekel et al. 1993, Dekel & Rees 1994). If $\Omega_0 = 1$, there are several possible solutions or implications from the baryon over-density problem.

(i) The X-ray emitting gas has been concentrated with respect to the dark matter and the total cluster masses are much higher, or there is clustering of dark matter on larger scales, *e.g.* in a mixed dark matter Universe.

(ii) The X-ray determined gas masses are over-estimated, *e.g.* due to clumping of the X-ray gas.

(iii) The current examples of large baryon over-densities in clusters are unrepresentative of clusters in general.

(iv) The cosmological constant, Λ, is non-zero and contributes to the density parameter such that $\Omega_0 = \Omega_{\rm matter} + \Omega_\Lambda = 1$ (*e.g.* see the review by Carrol, Press & Turner 1992).

(v) Ω_b can be higher if the Universe is inhomogeneous at the time of nucleosynthesis.

(vi) The new calculations of standard primordial nucleosynthesis or the primordial abundance measurements are incorrect, or they are very less tightly constrained, allowing $\Omega_b \sim 0.3h_{50}^{-2}$ (*e.g.* if some abundance determinations are incorrect).

Recent work on inhomogeneous nucleosynthesis (Jedamzik, Fuller, & Mathews 1994) now shows that (v) is not viable, and (vi) seems unlikely given the physics involved is well understood. Solution (ii) is unlikely to cause a significant discrepancy, as shown later in this paper (see also McHardy et al. 1990). We shall discuss solution (i), which implies that there are significant masses of gravitating matter outside the regions of the X-ray emitting gas. The main focus of this paper is to investigate point (iii) by determining gas masses to large radii in a number of clusters. Our determinations have been made from X-ray image-deprojection analysis of 19 clusters of galaxies which were observed with the *Einstein Observatory* Imaging Proportional Counter (IPC). These are X-ray luminous ($L_{\rm X\ bol} \gtrsim 5 \times 10^{44}$ erg s^{-1}) and moderately distant ($z > 0.05$) clusters which are easily covered by the IPC field of view, and have no strong contaminating sources to their surface brightness profiles. This enables their gas masses to be well determined out to between 1 to 2.5 Mpc.

2 DEPROJECTION ANALYSIS AND RESULTS

We have used the X-ray image deprojection technique (pioneered by Fabian et al. 1981). This method assumes a spherical geometry for the cluster, and enables the volume count emissivity from the hot intracluster gas to be determined as a function of radius. The properties of the intracluster medium (ICM) can then be determined after corrections for attenuation of the cluster emission due to absorption from intervening material, and assumptions on the form of the underlying gravitational potential of the cluster. Detailed descriptions and recent examples of the current analysis method and procedure can be found in the description of the analysis of *ROSAT* Position Sensitive Proportional Counter (PSPC) and High Resolution Imager (HRI) data, on A478, by Allen et al. (1993) and D. White et al. (1994), respectively.

This analysis differs from previous deprojection analyses, which have concentrated on investigation of the cooling flow properties of clusters, as such studies required relatively small radial bins to resolve the cooling time of the intracluster gas at the very centre of the cluster. We are interested in accurate determinations of the total gas masses in clusters to large radii and so large radial bins, which improve the signal-to-noise of the data, enable deprojection to greater radii. The clusters in our sample were selected to be bright and moderately distant so that the emission can be followed to sufficient radius within the field of view of the IPC. The X-ray emission of the cluster should also be relatively symmetrical with no significant contamination from sources which will produce significant errors in the gas mass determinations. Most of the clusters which we selected do appear fairly spherically symmetric and smooth in the central regions, although there are some clusters where the emission in the outer regions is less regular (notably A1763, A3186, A3266 and A3888). However, as these results are not significantly different from the clusters which appear very regular (such as A85, A478, A644, A1795 and A2009), we believe the results provide a good statistical indication of the baryon fraction in clusters, despite morphological details.

With the above criterion we formed our sample of 19 clusters, and obtained surface-brightness profiles from C. Jones, W. Forman and C. Stern at the Harvard-Smithsonian Center for Astrophysics. We selected IPC rather that HRI data for this analysis due its larger field of view and superior quantum efficiency. The poorer spatial resolution of the IPC, as we have noted is inconsequential. The point-spread function of the IPC, which is approximately 1 arcmin (Gaussian width), corresponds to relatively large radii at the moderate redshifts of the clusters in our sample. The data were corrected for the effects of the tele-

scope vignetting, and the background contributions were estimated from the region just outside the maximum radius of each deprojection. This ensures that our estimates of the cluster gas masses are conservative as there may be some cluster emission outside the selected maximum radius. The deprojection of the surface brightness profile of each cluster requires the additional information, shown in Table 1, such as the column density along the line-of-sight, the X-ray temperature and velocity dispersion of each cluster.

The total attenuation of X-rays from the cluster is dependent on the absorption (note we use photoelectric absorption cross-sections given by Morrison & McCammon 1983) within our Galaxy and intrinsic absorption. D. White et al. (1991b) have shown that many clusters appear to have intrinsic absorption, but as we do not have such information for our whole sample we use estimates for the Galactic contribution taken from the 21 cm determinations by Stark et al. (1992). The effect of possible excess absorption will be shown in Section 3.1, but we note here that our prescription leads to conservative gas mass estimates.

The *Einstein Observatory* IPC data do not have sufficient combined spatial and spectral resolution to enable an accurate empirical determination of the temperature profile, from which the gravitational potentials of the clusters may be determined. This means that the deprojection technique, which could otherwise be used to directly determine the total gravitational mass of the cluster as a function of radius, actually requires the form of the gravitational potential to be specified. The deprojection results are then calibrated using the only widely X-ray observed property of the intracluster medium — *i.e.* spatially averaged cluster temperatures from broad-beam detectors (Edge & Stewart 1991a and David et al. 1993).

The form of the gravitational potential that we have chosen is that of a true isothermal sphere. This produces comparatively conservative mass estimates (compared to a King-law distribution), and can be parameterised using observational data, such as the optical velocity dispersion. In our standard deprojection model we used a two-component true-isothermal potential, each parameterised by a velocity dispersion and core-radius, with one potential for the cluster and another for a central cluster galaxy. Only the cluster potential was varied; the galaxy potential was fixed with a galaxy velocity dispersion of $350\,\mathrm{km\,s^{-1}}$ and a core-radius of 2 kpc. The effect of uncertainties in the cluster velocity dispersion, the effect of the mass from a central galaxy, and the use of different gravitational mass distributions on the results were all investigated, and are discussed in Section 3.2. First we discuss the choice of cluster velocity dispersions and core radii.

The cluster velocity dispersions were chosen from the literature where available. However, when we could find no suitable value, or there appeared to be some problem obtaining a satisfactory deprojection results, we obtained a value from the following relationship between the velocity dispersion and observed X-ray temperature:

$$\sigma = 376\,[T_{\rm X}\,(\,\mathrm{keV})]^{0.528}\ \mathrm{km\,s^{-1}}\,. \qquad (1)$$

This relationship was determined (D. White et al. in preparation) using the ‘orthogonal distance regression’ algorithm (see the ODRPACK V2.01 software by Boggs et al. 1990, discussed in relation to astronomical data analysis by Feigelson & Babu 1992), and accounts for errors in both axes of the data — an essential feature when the errors in both dimensions are significant. The final velocity dispersions that were used, and the source of these values, are given in Table 1.

Suitable values for cluster core radii are more difficult to obtain than velocity dispersion values. Although they are available from the X-ray surface brightness profiles of clusters, and are less prone than optical values to contamination from sub-structure within the cluster, they can be affected by the presence of a cooling flow (which enhances the X-ray emission within the central 200 to 300 kpc, as shown by Forman & Jones 1984). Therefore we have not used the values for core-radii given in the literature, but used the core radius as a free parameter because it can significantly alter the shape of the gravitational mass distribution. As the best and most widely available cluster temperatures for most of our sample are only spatially-averaged values for the whole cluster, determined from broad-beam detectors, we vary the core-radius and outer pressure to produce a temperature profile that is as consistent with the observed value over as large a radius of the cluster as possible, *i.e.* a flat temperature profile. This tends to overestimate the temperature at the centre of a cluster in a cooling flow cluster, but will lead to conservative estimates of the gas mass, as $M_{\rm gas} \propto T_{\rm X}{}^{-1/4}$. The final selections of core radius and outer pressure used in each cluster are given in Table 2.

Note, we do not assign a particular significance to the core-radii that we have used in this analysis; it was essentially used as a parameter to obtain flat deprojected temperature profile for each cluster. This also produces conservative gas mass estimates, because the temperature at the centre will be hotter than expected in a cooling flow cluster. This may not represent the true form of the temperature profile, and our resulting core-radii may be somewhat misleading. This may explain some of the large core-radii, although it may also be due to unresolved physical substructure in the X-ray emission. We also note that as the baryon fraction varies with radius according to the core radius used, as can be seen in Fig. 1. We have therefore quoted our results at the maximum radius of each deprojection to ensure the results are not affected by the core-radii that were used.

The baryon fractions that we determine from the deprojected value of $M_{\rm gas}/M_{\rm grav}$ at the maximum radii are given in Table 2. They do not include the stellar contribution to the baryon content (perhaps an extra 5 per cent). The results indicate that there is a wide variation between approxi-

Table 1. Input Data.

No.	Cluster	z	Galactic 21 cm $N_{\rm H}$ ($10^{21}\,{\rm cm}^{-2}$)	Temperature (keV) Reference	Temperature (keV) Deprojected	Gravitational Potential $r_{\rm core}$ (Mpc)	Gravitational Potential σ (${\rm km\,s}^{-1}$)
1.	A85	$0.0521^{\S}$	0.30	$^{\star}6.2^{+0.4(0.2)}_{-0.5(0.3)}$	$(6.1^{+1.4}_{-0.3})$	0.10	$749^{\S}$
2.	A401	0.0748^{∞}	1.11	$^{\star}7.8^{+1.1(0.6)}_{-0.9(0.6)}$	$(8.3^{+1.2}_{-0.7})$	0.60	$\mathit{1112}^{T_{\rm X}}$
3.	A478	$0.0881^{\S}$	1.36	$^{\dagger}6.8^{+1.1(0.6)}_{-1.0(0.6)}$	$(7.2^{+1.8}_{-0.8})$	0.20	$904^{\S}$
4.	A545	0.1530^{∞}	1.14	$^{\star}5.5^{+\infty(6.2)}_{-2.8(2.1)}$	$(6.8^{+0.7}_{-4.3})$	0.65	$\mathit{925}^{T_{\rm X}}$
5.	A644	0.0704^{∞}	0.73	$^{\star}7.2^{+3.0(1.1)}_{-1.2(0.8)}$	$(7.2^{+0.7}_{-2.5})$	0.40	$\mathit{1017}^{T_{\rm X}}$
6.	A665	0.1816^{∞}	0.42	$^{\star}8.2^{+1.0(0.6)}_{-0.8(0.4)}$	$(9.4^{+0.2}_{-1.8})$	1.00	1201^{∞}
7.	A1413	0.1427^{∞}	0.20	$^{\star}8.9^{+0.5(0.3)}_{-0.5(0.3)}$	$(10.0^{+1.7}_{-2.3})$	0.50	$\mathit{1193}^{T_{\rm X}}$
8.	A1650	0.0840^{∞}	0.15	$^{\star}5.5^{+2.7(1.3)}_{-1.5(1.0)}$	$(6.1^{+0.6}_{-0.8})$	0.35	$\mathit{925}^{T_{\rm X}}$
9.	A1689	0.1810^{∞}	0.19	$^{\star}10.1^{+2.7(54)}_{-1.5(1.0)}$	$(10.9^{+0.2}_{-0.9})$	0.40	$\mathit{1275}^{T_{\rm X}}$
10.	A1763	$0.1870^{\diamondsuit}$	0.09	$^{\star}6.9^{+\infty}_{-3.6(1.9)}$	$(7.1^{+0.6}_{-3.2})$	0.70	$\mathit{1043}^{T_{\rm X}}$
11.	A1795	$0.0621^{\S}$	0.12	$^{\dagger}5.1^{+0.4(0.2)}_{-0.5(0.3)}$	$(5.6^{+0.1}_{-0.8})$	0.20	$773^{\S}$
12.	A2009	0.1530^{∞}	0.33	$^{\star}7.8^{+\infty(4.4)}_{-2.9(2.1)}$	$(8.0^{+0.5}_{-0.5})$	0.40	$\mathit{1112}^{T_{\rm X}}$
13.	A2029	$0.0765^{\S}$	0.24	$^{\star}7.8^{+1.4(0.8)}_{-1.0(0.7)}$	$(8.3^{+1.0}_{-3.1})$	0.30	$\mathit{1112}^{T_{\rm X}}$
14.	A2142	0.0899^{∞}	0.39	$^{\dagger}11.0^{+2.0(1.2)}_{-0.7(0.4)}$	$(10.4^{+1.0}_{-4.9})$	0.40	$1295^{\bullet}$
15.	A2163	$0.2030^{\clubsuit}$	1.10	$^{\star}13.9^{+1.1(0.7)}_{-0.8(0.5)}$	$(14.2^{+1.1}_{-11.3})$	0.60	$\mathit{1509}^{T_{\rm X}}$
16.	A2319	$0.0559^{\spadesuit}$	0.86	$^{\star}9.9^{+1.4(0.8)}_{-1.1(0.7)}$	$(11.9^{+1.3}_{-3.0})$	0.60	$\mathit{1261}^{T_{\rm X}}$
17.	A3186	$0.1270^{\clubsuit}$	0.60	$^{\ddagger}5.9$	$(6.7^{+1.6}_{-3.0})$	0.50	$\mathit{960}^{T_{\rm X}}$
18.	A3266	$0.0545^{\heartsuit}$	0.30	$^{\star}6.2^{+0.6(0.5)}_{-0.6(0.4)}$	$(6.8^{+0.6}_{-1.1})$	0.80	$\mathit{985}^{T_{\rm X}}$
19.	A3888	$0.1680^{\heartsuit}$	0.11	$^{\ddagger}7.9$	$(7.9^{+0.3}_{-1.0})$	0.50	$\mathit{1120}^{T_{\rm X}}$

This table contains the input data required for the cluster deprojections. The first temperatures given are reference values (with 5th and 95 percentile confidence limits and 1σ standard deviations in the brackets) obtained from the literature. In the next column are the spatially-averaged emission-weighted ($0.4-4$ keV) temperatures from the deprojected temperature profiles (these are median values with 10th and 90th percentile limits given in brackets). A comparison of these two columns shows the accuracy of the deprojection calibration with respect to the reference temperatures. The velocity dispersion values written in italics with the superscript $T_{\rm X}$ refer to values interpolated from the X-ray temperature values using equation stated in the main text. Note, we have used X-ray temperature interpolated velocity dispersions for A401, A2009 and A2029, as we were unable to obtain a flat temperature profile from the literature values. The velocity dispersion for A401 was reduced from $1290^{\infty}\,{\rm km\,s}^{-1}$, for while A2009 and A2029 the velocity dispersion was increased from $804^{\infty}\,{\rm km\,s}^{-1}$ and $786^{\S}\,{\rm km\,s}^{-1}$. The superscripts refer to: $\star$ David et al. (1993); † Edge & Stewart (1991a); ‡ Forman & Jones (private communication); § Zabludoff, Huchra & Geller (1990); ∞ Struble & Rood (1991); • Quintana & Lawrie (1982); ♣ Arnaud et al. (1992); ◇ Noonan (1981); ♡ Abell, Corwin & Olowin (1989); and ♠ Stocke et al. (1991).

mately 10 and 30 per cent, although some of this variation is due to an apparent trend for increasing baryon fraction with radius, as shown in Fig. 2. A linear regression to the data in this diagram (shown by the dashed line) indicates that the baryon fraction may be consistent with $\Omega_{\rm b,max} \leq 0.06$ only at the very centre, but the mean value of the data points is much higher than the standard primordial nucleosynthesis value. We note that Fig. 2 does not account for errors in the gravitational potential from the velocity dispersion, but we shall address this point in Section 3.2.

The uncertainty from the core radius, and other parameters, on the determination of the baryon fractions has been assessed using the Abell 478 data as a control data set. The results of these tests, which will be discussed in the following section and shown in Table 3, indicate that the gravitational potential of the cluster provides the main uncertainty in the baryon fraction determinations.

3 BARYON FRACTION UNCERTAINTIES

As the deprojection estimates of the cluster baryon fraction are given by $M_{\rm gas}/M_{\rm grav}$, we have estimated the susceptibility of the deprojection results to uncertainties in $M_{\rm gas}$ and $M_{\rm grav}$ resulting from changes in the input parameters for an individual cluster. We have also estimated the uncertainties in the baryon fraction due to $M_{\rm grav}$ using the observational errors in the X-ray temperatures.

3.1 Gas mass uncertainties

The deprojection method produces gas mass estimates that are statistically very well determined. We assume that the emission in the outer regions of clusters arises from thermal emission rather than non-thermal processes, as there is no evidence for significant non-thermal emission at large radii

Table 2. Results

No.	Cluster	R_0 (Mpc)	dR (Mpc)	Mass (10^{14} M$_\odot$) Gas	Grav	Mass Ratio ($M_{\rm gas}/M_{\rm grav}$ %) ($R \leq 1$ Mpc)	($R \leq R_0$)
1.	A85	1.415	0.101	0.87 ± 0.06	4.64	17.3 ± 1.1	18.8 ± 1.3
2.	A401	1.265	0.141	1.32 ± 0.07	10.1	12.8 ± 0.4	13.0 ± 0.7
3.	A478	1.951	0.163	2.38 ± 0.21	9.28	23.1 ± 0.9	25.6 ± 2.2
4.	A545	1.815	0.259	1.91 ± 0.25	10.6	17.1 ± 1.6	18.1 ± 2.4
5.	A644	1.198	0.133	0.95 ± 0.06	9.06	10.6 ± 0.6	10.5 ± 0.6
6.	A665	2.376	0.297	4.37 ± 0.46	22.1	18.1 ± 1.0	19.8 ± 2.1
7.	A1413	1.715	0.245	1.83 ± 0.23	15.9	10.8 ± 1.1	11.5 ± 1.4
8.	A1650	1.090	0.156	0.75 ± 0.08	6.37	11.8 ± 1.2	11.8 ± 1.2
9.	A1689	1.481	0.296	2.12 ± 0.16	15.5	13.0 ± 0.5	13.7 ± 1.0
10.	A1763	1.823	0.304	2.61 ± 0.22	13.2	17.6 ± 1.2	19.8 ± 1.7
11.	A1795	1.426	0.119	1.13 ± 0.08	5.49	18.7 ± 1.1	20.6 ± 1.5
12.	A2009	1.297	0.259	1.44 ± 0.10	10.6	13.4 ± 0.5	13.6 ± 0.9
13.	A2029	1.291	0.143	1.26 ± 0.11	10.3	11.9 ± 0.8	12.3 ± 1.1
14.	A2142	1.931	0.276	2.84 ± 0.15	20.1	11.9 ± 0.3	14.1 ± 0.6
15.	A2163	2.264	0.323	5.46 ± 0.49	32.5	14.4 ± 1.0	16.8 ± 1.5
16.	A2319	1.402	0.108	1.73 ± 0.12	14.2	11.9 ± 0.8	12.2 ± 0.8
17.	A3186	1.508	0.188	1.76 ± 0.23	9.50	15.6 ± 1.9	18.5 ± 2.4
18.	A3266	1.420	0.114	1.42 ± 0.07	9.07	15.4 ± 0.4	15.7 ± 0.8
19.	A3888	1.118	0.279	1.20 ± 0.15	8.66	13.9 ± 1.8	13.9 ± 1.8

This table summarizes the deprojection results, where R_0 is the outer radius of the deprojection, dR is the bin size. The gas and gravitational results are plotted against R_0 in Fig. 7. The baryon fractions within 1 Mpc and the total region of each deprojection are given in the last two columns. Note the observational errors in the velocity dispersion are not available for all the clusters, and so are not quoted. The uncertainty in $M_{\rm gas}$ and $M_{\rm gas}/M_{\rm grav}$ are 1σ standard deviation values, resulting from the statistical uncertainty in the X-ray data.

from the radio waveband. The main uncertainty in the gas masses arises from the intrinsic X-ray luminosity of a cluster, *i.e.* through the estimate of the distance to the cluster, intervening absorption, spherical symmetry, and the effect of clumping in the intracluster gas. All these points are addressed below.

The effect of ellipticity in the cluster X-ray emission has been investigated by D. White et al. (1994) in their analysis of *ROSAT* HRI data on A478. They found that the ellipticity of $(1 - b/a) = 0.2$ in the X-ray emission produced an average (and 1σ) value of $M_{\rm gas} = (4.6 \pm 0.5) \times 10^{13}$ M$_\odot$ (within 0.5 Mpc) from the deprojection of four sectors, as compared to $M_{\rm gas} = (4.8 \pm 0.2) \times 10^{13}$ M$_\odot$ from an azimuthal average. Thus, within errors the effect of the spherical symmetry assumption is negligible. We also note that, although a cluster may appear spherically symmetric in projection, it may be extended in the line of sight. However, for a constant luminosity $L_{\rm X} \propto {M_{\rm gas}}^2/V$ the volume V would have to be increased by a factor of 16 to eliminate baryon over-densities of 4. Similarly, the accuracy of the background subtraction, which affects the luminosity estimate, would have to be wrong by a factor of 16 to reduce a baryon fraction of 25 per cent to the universal value of ≤ 6 per cent. We therefore do not consider spherical asymmetries, either tangential or elongation along the line of sight, or background subtraction uncertainties, to be important effects in the baryon overdensities in clusters, especially if the baryon overdensities are shown to be common in a statistical sample of clusters such as ours.

The uncertainty in the gas masses from the distance is obviously dependent on cosmological parameters and the cluster redshift (we have adopted a Hubble constant of $H_0 = 50 h_{50}$ km s^{-1} Mpc^{-1} in the general analysis). The expected dependences of the masses on H_0 are approximately $M_{\rm gas} \propto h_{50}^{-5/2}$ (for a constant radial density profile in the cluster), $M_{\rm grav} \propto h_{50}^{-1}$ (at radii outside the core of an

Figure 1.

This diagram shows that differing mass fraction profiles obtained with differing core radii (0.2, 0.5 and 1.0 Mpc) for the gravitational mass distribution. This example is for the Abell 478 data, where the core radius used to give a flat temperature profile was 0.2 Mpc. This is also approximately the core radius determined from a comparison of a deprojection and spectral analysis of *ROSAT* PSPC data (Allen et al. 1993). We note that outside the core region of each potential the mass fraction profiles are approximately flat, and more importantly, tend to the same result.

Figure 2.

This diagram shows the baryon fraction ($M_{\rm gas}/M_{\rm grav}$) at the outer radius of each deprojection. The dashed line show a best-fitting linear function of $M_{\rm gas}/M_{\rm grav} = 0.0579 + 0.0556R$. This is clearly inconsistent with the standard nucleosynthesis value of < 6 per cent, indicating by the dot-dashed line. Note the dashed line also shows an increase in the baryon fraction with radius. Observational errors on $M_{\rm grav}$ are not included in this plot but the effect on $M_{\rm gas}/M_{\rm grav}$ is estimated in Section 3.2 from Fig. 6.

Table 3. Test Parameters

Test No.	Cosmology H_0	q_0	z	N_{H} (10^{21} cm^{-2})	T_{X} (keV)	ϕ G-C	dM/dR ($\mathrm{M}_\odot$ kpc^{-1})	σ (km s^{-1})	r_{core} (Mpc)	P_0 (10^4 K cm^{-3})	M_{gas} (10^{14} $\mathrm{M}_\odot$)	M_{grav} (10^{14} $\mathrm{M}_\odot$)	$M_{\mathrm{gas}}/M_{\mathrm{grav}}$ ($\times$100%)
0.	50	0.0	0.0881	1.36	6.8	ISO-ISO	N/A	904	0.20	1.5	2.38 ± 0.21	9.28	25.6 ± 2.2
1.	100								0.10		0.84 ± 0.08	4.65	18.2 ± 1.6
2.		0.5									2.30 ± 0.20	9.11	25.2 ± 2.2
3.			0.0890								2.44 ± 0.21	9.35	26.1 ± 2.3
4.			0.0872								2.32 ± 0.20	9.21	25.2 ± 2.2
5.				2.50							2.59 ± 0.23	9.28	28.0 ± 2.5
6.					7.9					2.0	2.38 ± 0.20	9.28	25.7 ± 2.2
7.					5.8					1.0	2.38 ± 0.21	9.28	25.6 ± 2.3
8.						KNG-KNG				2.0	2.38 ± 0.21	7.08	33.6 ± 2.9
9.						NO-ISO					2.38 ± 0.21	8.10	29.4 ± 2.6
10.						NO-LM	5.0	N/A	N/A		2.38 ± 0.21	10.2	23.3 ± 2.0
11.								1165	0.50	1.0	2.39 ± 0.21	17.1	13.9 ± 1.2
12.								764	0.15	3.0	2.39 ± 0.20	6.67	35.8 ± 3.0

This table summarizes the effects of uncertainties in various input parameters used in the deprojection analysis on the results (shown in the last three columns). The tests have been applied to the A478 data, and the variations should be compared with the standard results shown in the first row (test number 0). The largest reduction in the mass ratio is produced by lowering the velocity dispersion to the 1σ lower limit given by Zabludoff, Huchra & Geller (1990). The parameter labeled ϕ indicates the galaxy-cluster combined potential used; ISO indicates a true isothermal potential, KNG a King Law potential, NO a null contribution, and LM indicates a linear mass model. The numbers for the gravitational potentials are: σ for the velocity dispersion of the cluster and r_{core} for the core radius, or dM/dR for the amount of mass in the linear mass model. P_0 is the pressure used at R_0 to obtain the correct deprojected temperature profile (in conjunction with the core radius where applicable). N/A indicates the entry was not applicable to the potential used in that test.

isothermal sphere), and therefore the baryon fraction should change as $M_{\mathrm{gas}}/M_{\mathrm{grav}} \propto h_{50}^{-3/2}$. However, we have found that a deprojection with a different Hubble constant requires a gravitational potential with a proportionately smaller core radius to obtain the same temperature profile as that obtained with a smaller Hubble constant. Test number 1 of Table 3 shows that with $h_{50} = 2$ the change in M_{grav} is in agreement with that expected for a cluster that is half as distant and with a core-radius half as large. The corresponding change in M_{gas} is less than the expected value of $0.42 \times 10^{14}\,\mathrm{M}_\odot$, because the required change in core radius, for a flat temperature profile, results in a larger X-ray luminosity and gas content in the central regions of the cluster. Therefore, because the changes in the Hubble constant force a recalibration of the deprojection results, the Hubble constant uncertainties lead to a smaller changes in the baryon mass fraction than would be expected. The uncertainty in q_0 and the redshift of a cluster produce comparatively small changes, as shown in test 2 for $q_0 = \frac{1}{2}$, or tests 3 and 4 for the statistical uncertainties in the redshift of A478.

Although the Hubble constant provides the greatest uncertainty in the gas mass determinations, it does not eliminate the large baryon over-densities. An unreasonably small Hubble constant would be required to reduce them to the standard primordial nucleosynthesis values, because this also depends on H_0 as $\Omega_{\mathrm{b}} \leq 0.06 h_{50}^{-2}$. However, as Steigman (1987, 1989) has noted, a more useful limit may be obtained by requiring that the gas mass does not exceed the total mass of the cluster. Assuming that $M_{\mathrm{gas}}/M_{\mathrm{grav}} \propto h_{50}^{-3/2}$, then we obtain a lower limit on the Hubble constant of $H_0 = 22$ km s^{-1} Mpc^{-1}.

The gas mass determinations also depend on the estimate of the absorption of X-rays emitted from the cluster. We have already noted that intrinsic absorption may occur in some clusters, but we have used Galactic column densities determined from 21 cm measurements throughout to give a consistent sample of column density determinations. As these represent minimum estimates for the total column densities, we have tested for the effect of excess absorption on the baryon fraction. We expect that the baryon fraction should increase with the intrinsic luminosity, and therefore gas masses will be larger rather than smaller. A478 provides an ideal example, as the excess absorption in this cluster has been well studied (D. White et al. 1991b, Johnstone et al. 1992, Allen et al. 1993). In test 5 of Table 3 we show that an addition of 1.1×10^{21} cm^{-2} above the Stark et al. (to the value determined by Allen et al. from their spectral fits of the *ROSAT* PSPC data on A478 of 2.5×10^{21} cm^{-2}) produces approximately a 10 per cent increase in the gas mass.

One further point in the determination of gas masses from X-ray data that we discuss is the effect of clumping

Figure 3.

These plots show: (a) the error in the gas mass estimate, (b) the emission-weighted temperature, when the X-ray emission is assumed to be from a single-phase medium but there are actually two phases. The single-phase temperature is assumed to be k$T_{\mathrm{ref}} = 7$ keV. The main-phase temperature is k$T_1 = 7$ keV (with an abundance of $Z_1 = 0.4\,\mathrm{Z}_\odot$), and the secondary-phase temperature is varied between k$T_2 = (0.01 - 10) \times$ kT_{ref}. The separate lines are for volume filling factors of the secondary phase of V_2: 0.0 – solid (flat), 0.01 – dash, 0.05 – dash-dot, 0.10 – dot, 0.70 – dash-dot-dot-dot, 0.5 – solid.

Figure 4.

These plots are similar to those in Fig. 3 where the single-phase temperature is assumed to be k$T_{\mathrm{ref}} = 7$ keV, but here the main-phase temperature is actually k$T_1 = 15$ keV and the secondary-phase abundance is $Z_2 = 2\,\mathrm{Z}_\odot$.

in the intracluster gas. We have estimated the error in the determinations of the gas mass that could arise when the gas is assumed to be a single-phase medium, but in actuality the gas is multiphase. Two phases have been considered, and the combined emission is forced to produce a fixed total number of counts $F_{0.4-4\,\mathrm{keV}}$ in a waveband from $0.4-4\,\mathrm{keV}$ (*i.e.* a top-hat approximation to the response of the IPC). We then select a reference temperature for the single phase estimation and compare this mass with the mass that we would estimate if the gas had two-phases with different temperatures and volume filling-factors. The masses in the two phases are given by solving the following equation assuming pressure equilibrium between the two phases:

$$F_{0.4-4\,\mathrm{keV}} \propto n_1^2 V_1 \int_{0.4\,\mathrm{keV}}^{4\,\mathrm{keV}} \frac{\Lambda(\mathrm{k}T_1)}{E} dE + n_2^2 V_2 \int_{0.4\,\mathrm{keV}}^{4\,\mathrm{keV}} \frac{\Lambda(\mathrm{k}T_2)}{E} dE \;, \qquad (2)$$

where the subscript number refers to the two phases, n is the electron number density, kT is the temperature variable, V is the volume fraction, and E is photon energy in the integral that evaluates the total number of counts from the cooling function Λ in the specified waveband. We note that equation 2 takes no account of absorption or the effect of cluster redshifts. Note, we also assume pressure equilibrium between the two phases, otherwise a mechanism is required to prevent the cooler gas from expanding and mixing into the hotter gas.

In Fig. 3(a) we show the error in the gas mass determination when a single phase of temperature $\mathrm{k}T_{\mathrm{ref}} = 7\,\mathrm{keV}$ is assumed. The lines show the mass error when there is one component of temperature $\mathrm{k}T_1 = 7\,\mathrm{keV}$ and a secondary phase which is varied between $\mathrm{k}T_2 = (0.01 - 10) \times \mathrm{k}T_{\mathrm{ref}}$. The different lines show the mass error for volume fractions of the secondary phase, $V_2 = 0 - 0.5$. It can be seen that a baryon over-density of a factor of 2 could be eliminated by over-estimates in the gas mass determination, if the secondary phase filled less than approximately 40 per cent of the total volume, and had a temperature between approximately 0.8 and $1\,\mathrm{keV}$ (depending on the exact value of V_2). However, from Fig. 3(b), we can see that the corresponding emission-weighted temperature from the combined medium could only be as high as approximately $1.5\,\mathrm{keV}$, irrespective of V_2, so that it is unlikely such errors in the gas mass could be made as the temperature was assumed to be $\mathrm{k}T_1 = 7\,\mathrm{keV}$. Observational uncertainties would usually rule out such a large discrepancy.

From a slightly different perspective, one can ask if we can obtain sufficient gas mass overestimates when the emission-weighted temperature from the combined emission is close to that expected from a single-phase gas. In Fig. 4 we show the results when the gas is thought to have a single-phase temperature of $\mathrm{k}T_{\mathrm{ref}} = 7\,\mathrm{keV}$, but there is actually a component at $\mathrm{k}T_1 = 15\,\mathrm{keV}$ (of the same abundance of $Z_1 = 0.4\,\mathrm{Z}_\odot$) and a second component, again between $\mathrm{k}T_2 = (0.01 - 10) \times \mathrm{k}T_{\mathrm{ref}}$ (this time with an abundance of

Figure 5.

This diagram shows the different gravitational mass distributions. The standard deprojection results employ the true isothermal potentials (solid line). We note that the King law underestimates the mass at outside 8 to 10 core-radii (which is =0.2 Mpc in this example).

$Z_2 = 2.0\,\mathrm{Z}_\odot$). Very large overestimates can be produced, but a factor of two overestimation is not obtained unless the emission-weighted temperature is allowed to be as low as approximately $5\,\mathrm{keV}$ (for $V_2 = 0.01$). In this case the average abundance would be about $0.5 - 0.6\,\mathrm{Z}_\odot$, which is not unreasonable compared to the $Z_{\mathrm{ref}} = Z_1 = 0.4$ that would be assumed, and the fraction of mass in the cooler phase is approximately 10 per cent (the luminosity contribution is about be 70 per cent).

We can apply this scenario of significantly different temperature phases to a cluster of a similar emission weighted temperature. A1763 has an emission-weighted temperature of $\mathrm{k}T \sim 7\,\mathrm{keV}$, and a deprojected gas mass of $2.6 \times 10^{14}\,\mathrm{M}_\odot$ (within 1.8 Mpc radius). Therefore, from our example, we would expect $1.3 \times 10^{13}\,\mathrm{M}_\odot$ in a cooler phase to produce a 50 per cent overestimate of the gas mass. This amount of cooler gas cannot be contained within the interstellar medium of giant elliptical galaxies (which have the required temperature of approximately $1\,\mathrm{keV}$), as the mass in the cool gas is equivalent to approximately a thousand giant elliptical galaxies, which is clearly unreasonable. Thus the majority of the cooler gas would have to be in the intracluster medium, isolated from the destructive processes of the hotter phase by magnetic fields. The problem with this scenario is that observations already appear to rule out variations of more than a factor of two in the intracluster gas, as we discuss below.

In summary, large gas mass overestimations can occur when there is significant amounts of cooler gas at $\mathrm{k}T \lesssim 1\,\mathrm{keV}$ with line emission which enables the same count emissivity to be produced by a smaller mass of gas. As the effect is due to the lines, the abundance of the intracluster gas also influences the possibility of mass determination errors. However, the emission-weighted temperature also decreases with abundance, as most of the emission comes from the cooler phase, and the resulting effect of abundance variations is that the gas mass over-estimates are very nearly constant for a given range of the emission-weighted temperature. We note that, in a spectral analysis a contribution from a cool phase should be easily discernible, however our deprojection analysis is a broad-band analysis and cannot discriminate between combined spectra of various temperature which produce similar count emissivities.

Although we cannot rule out such disparate temperatures from our imaging analysis, a spectral analysis of *Ginga* and *EXOSAT* data on the Perseus cluster (Allen et al. 1992) only allows temperature variations of a factor of approximately two. Also, a spectral analysis of the A478 cluster

Figure 6.

These plots show how we have estimated the effect of uncertainties in the gravitational potential using the errors in the observed X-ray temperatures (from 13 clusters where the temperature errors are measured, and symmetric to within 2 keV). The uncertainty in the gravitational mass has been estimated by propagating the (1σ) errors in the observed X-ray temperature to the baryon fraction at 1 Mpc, as shown in (a). Assuming that the errors are symmetric and Gaussian we have then determined the cumulative probability, as shown in (b), from which we estimate that the cluster baryon fraction at 1 Mpc has a median value of 13.8 per cent, with 5th and 95th percentile limits of 10.0 and 22.3 per cent.

out to 2 Mpc (Allen et al. 1993) indicates that a 1 keV component cannot be significant in this cluster, as the best-fit emission-weighted temperature is consistent with the broad-beam value (6.8 keV), and is above 4 keV at the 90 per cent confidence level. Only in the central regions of the cooling flow, and between $1-2$ Mpc is the lower-limit around 1 keV (but the best fit is around 4 keV). Thus, within 1 Mpc where the temperature is well constrained and there is still a baryon over-density problem, the results indicate that a cool component is not significant. We expect *ASCA* to be able to rule out such variations to much larger radii.

One further point is that the baryon overdensities are common to the whole sample and do not appear to be dependent on the Galactic column density. If clumping were responsible for gas mass overestimates then we would have expected clusters such as A478, which have large Galactic column densities, to have smaller than average baryon overdensities because we would see little of the sub-1 keV emission would be responsible for the overestimations.

From our investigations into the required conditions for significant gas mass overestimations, and spectral observations of specific clusters, we conclude that clumping cannot explain the baryon overdensities in clusters.

3.2 Gravitational mass uncertainties

We have shown that the gas mass uncertainties are unlikely to reduce the cluster baryon fractions to the 6 per cent upper limit obtained from standard primordial nucleosynthesis. However, the gravitational potential is the most uncertain component in the calculation and we now discuss its uncertainties. The deprojection results are changed by altering the gravitational potential to give a temperature that is consistent with the observed broad-beam values. In tests 6 and 7 of Table 3 we can see that the statistical uncertainties in the temperature (for A478) produce comparatively small changes in the results, so that individual baryon fraction uncertainties will be probably dominated by the form of the potential that is chosen to obtain this temperature, rather than errors in this temperature determination.

We have investigated the effect of changes in the gravitational potential, *e.g.* for a King-law density distribution, the gravitational contribution from the central galaxy, changing the form of the gravitational potential, and the statistical uncertainties in the optical velocity dispersion of the cluster. In the first case, test 8 shows that replacing both the galaxy and cluster potentials with King-law distributions increases the baryon fraction estimate. The reason for this is shown in Fig. 5 where we have plotted several different mass distributions (appropriate for Abell 478, *i.e.* a velocity dispersion of 904 km s^{-1} and the core-radius which we used of 0.2 Mpc). The King approximation provides a good description for the mass distribution within 10 core-radii (<2 Mpc), but outside this region the King law clearly underestimates that total gravitational mass compared to the true isothermal potential. Although we have no particular reason to believe the cluster should follow a true isothermal potential at large radii (especially if the cluster in not relaxed), we use the true isothermal potential to provide conservative baryon fraction estimates. In test 9 we show that when the mass of the central galaxy is neglected, a larger baryon fraction is estimated for the cluster. When the remaining cluster potential is changed to a linear mass distribution (test 10), similar results to the standard result are obtained.

The major change in the gravitational mass estimates, and therefore the baryon fraction, actually arises from the uncertainties in the velocity dispersion, as shown in tests 11 and 12. The statistical uncertainties (for A478; Zabludoff, Huchra & Geller 1990) indicate that the cluster baryon fraction can be reduced from 26 per cent to 14 per cent when the (1σ) upper limit on the velocity dispersion is used (+261 km s^{-1}), but it is then very difficult to obtain a flat temperature profile, and the baryon fraction has still not been reduced to less than 6 per cent. To reduce all the baryon overdensities to <6 per cent would require that we use high velocity-dispersions for all the clusters, and would then produce unsatisfactory temperature profiles. This seems to be an unlikely solution to the baryon overdensity problem, especially as optical velocity dispersions are, if anything, usually overestimated due to substructure in clusters.

We have attempted to estimate the uncertainty in the results due to the gravitational potential mass using the error in the reference (observed) temperatures. To estimate the effect of uncertainties in the velocity dispersion we have plotted the baryon fraction within a consistent radius of 1 Mpc (see Table 2) against the observational X-ray temperature (see Table 1). We have only included those data where the X-ray temperature has been measured and its uncertainties (the standard deviation errors) are reasonably symmetric (*i.e.* the positive and negative errors are similar within 2 keV). This eliminates A545, A1689, A1763, A2009, A3186 and A3888. Using this refined sample of 13 clusters we have propagated the uncertainty in the temperature onto the uncertainty in the baryon fraction, as shown in Fig. 6(a). (Note, $M_{\rm gas}$ is not significantly affected by uncertainties in the X-ray temperature.) To then estimate confidence limits on the baryon fraction with 1 Mpc we have treated the errors as Gaussian, and determined the cumulative probability as

Figure 7.

The gas masses (squares) at the outer radius of the deprojection of each cluster are plotted together with the total gravitational masses (triangles). The *solid* line shows a fits to the gas masses, $M_{\rm gas} = 6.7{\times}10^{13} R^2_{\rm Mpc}$, which predicts gravitational masses (*dot-dash* line) of $M_{\rm grav}\,(\Omega_{\rm b} = 0.06) = 1.1 \times 10^{15} R^2_{\rm Mpc}$, if $\Omega_{\rm b}/\Omega_0 = 0.06$. The actual gravitational masses in the deprojection results are fit with $M_{\rm grav}{}' = 4.7 \times 10^{14} R^2_{\rm Mpc}$ (*dashed* line) if the same index as the gas mass is used, or $M_{\rm grav}{}'' = 5.3 \times 10^{14} R^{1.79}_{\rm Mpc}$ if the power law has a free-fit index (*dotted* line). (Errors on the data points are 1 standard deviation.)

a function of baryon fraction, as shown in Fig. 6(b). The diagram clearly shows that although there is a wide variation in the baryon fraction, it is very unlikely (*i.e.* a probability of 10^{-4}) that at least one cluster from a similar sample has a baryon fraction at 1 Mpc of $\Omega_{\rm b,max} \leq 0.06$. We estimate that the median baryon fraction at 1 Mpc is 13.8 per cent with 5th and 95th percentile confidence limits of 10.0 and 22.3 per cent.

4 DISCUSSION

The results, as shown in Fig. 2, from our deprojection analysis of 19 clusters of galaxies indicate that the baryon fraction in clusters is inconsistent with the mean baryon fraction of the Universe predicted from standard primordial nucleosynthesis calculations, if $\Omega_0 = 1$, as first noted by S. White & Frenk (1991) for the Coma cluster. The diagram also shows a trend for increasing baryon fractions with radius, and indicates that the cluster baryon fraction could be consistent with the universal value of < 6 per cent at the very centre of clusters, but not further out.

Our determinations of the baryon content in clusters are not compromised by the uncertainties in our analysis. The gas masses are extremely well determined, and overestimates due to clumping appear unlikely to be able to simultaneously reduce the baryon fractions significantly and produce observationally consistent emission-weighted temperatures. The uncertainty in H_0 would require an unreasonably small H_0 to reduce the cluster baryon fractions to < 6 per cent ($\Omega_0 = 1$), and a lower limit of $H_0 = 22$ km s^{-1} Mpc^{-1} is obtained by allowing all the mass of the clusters to be in gas (see also Steigman 1987, 1989). Possible excess absorption in clusters only increases the gas mass estimates. The main uncertainty in the cluster baryon fractions probably arises from the uncertainties in the total gravitational mass, which are dominated by the cluster velocity dispersion values. The optical determinations of all the velocity dispersions would be have to be underestimated, which is somewhat contrived, and is also contrary to overestimates expected from optical determinations if the clusters have undetected substructure.

Since our results indicate that baryon fractions at 1 Mpc are typically $10-20$ per cent in clusters, then the simplest solution to the conflict with standard primordial nucleosynthesis may be that $\Omega_0 \lesssim 0.3$. As there is evidence for $\Omega_0 = 1$ (see the Introduction) we shall first discuss the implications that arise from assuming standard primordial nucleosynthesis when $\Omega_0 = 1$. (Note we ignore the fact that $q_0 = \frac{1}{2}$ when $\Omega_0 = 1$, whereas our results are for $q_0 = 0$. Test 2 in Table 3 indicates that q_0 has little affect on the results.)

Using the results given in Table 2 we have plotted, in Fig. 7, the gas and gravitational masses against the maximum radius of each deprojection. We note that if all the cluster deprojections are extended to the surface brightness of the background, then we would expect the gas masses at the maximum radii to follow an R_0^2 dependence, and indeed fitting a power-law function to the gas masses at the maximum radius indicates that the index is 2.2 with 90 per cents confidence limits of ± 0.17. We have therefore obtained gas masses approaching the maximum detectable radii for these data. Forcing an index of 2, and fitting a power law to the gas masses gives the fit of $M_{\rm gas} = 6.7 \times 10^{13} R^2_{\rm Mpc}$ shown by the *solid* line. The corresponding total masses used in the deprojection analysis, fitted with the same radial dependence, gives $M_{\rm grav}{}' = 4.7 \times 10^{14} R^2_{\rm Mpc}$, shown as the *dashed* line. If the gravitational masses are fitted with the radial dependence as a free parameter, then we find that $M_{\rm grav}{}'' = 5.3 \times 10^{14} R^{1.79}_{\rm Mpc}$, shown as the *dotted* line. This again indicates that the baryon fraction increases with radius, as already found in Fig. 2. If we then assume that $\Omega_{\rm b}/\Omega_0 = 0.06$ in clusters, and return to the same radial dependence as the gas masses, then the expected total gravitational mass is given by $M_{\rm grav}\,(\Omega_{\rm b} \leq 0.06) = 1.1 \times 10^{15} R^2_{\rm Mpc}$, shown as the *dot-dash* line.

From this we can see that, if we use the mean baryonic fraction of < 6 per cent to predict the total gravitational masses from gas masses, then we overpredict masses with respect to the virial values, *e.g.* for A665 the predicted mass is approximately 5.7×10^{15} M$_\odot$ within 2.4 Mpc. This is larger than considered from current theories of cluster formation, which would give a total mass of 2.8×10^{15} M$_\odot$ for A665 [from equation $kT/(4\,{\rm keV}) = (M/10^{15}\,{\rm M}_\odot)^{2/3}$ in Henry et al. 1992]. This total mass is more in line with that expected for a very much hotter cluster, such as A2163 at 13.9 keV. We also note that current theories of the formation of large-scale structure and cluster of galaxies may have problems explaining the apparently common occurrence of large baryon overdensities. For the median and 5th and 95th percentile confidence limits that we have placed on the baryon fraction within 1 Mpc, the overdensity is probably at least $2\Omega_{\rm b}$.

If clusters are truly overdense in baryons then, as highlighted by Fabian (1991) from the Shapley Supercluster data, then how are the extra baryons accumulated from the surrounding volume at the maximum mean density of 6 per cent for the Universe? In A665 the gas mass is approximately 5.4×10^{14} M$_\odot$ within 2.4 Mpc, and therefore the size of the region with the equivalent mass of baryons for a Universe of density $\Omega_{\rm b} \leq 0.6$ is 31 Mpc — a factor of 13 in radius, or greater than 2×10^3 in volume. The require-

ment of such large regions, to provide a source of baryons for such overdensities, may be too large to enable the concentration to occur within a Hubble time and would rule out self-gravitational accumulation of baryons as a valid mechanism to concentrate the baryons. This is the real problem of baryon overdensities in clusters, as it is independent of the uncertainties in the gravitational mass estimates in this analysis. However, even if we assume that sufficient baryons *can* be accumulated within the cluster, we still have to explain how the baryons appear be concentrated at the centre of a cluster with respect to the overall dark matter distribution. In Fig. 8 we show a schematic diagram of the gas and gravitational mass distributions that could give rise to large baryon fractions within the central $\sim 3\,\mathrm{Mpc}$, decreasing to a baryon fraction consistent with the universal average at larger radius. [We note, with the mass fractions determined from the deprojection results and the β values for clusters (Forman & Jones 1984), both indicate an increase of the gas to gravitational mass fraction increases with radius, over the observed regions of clusters, *i.e.* $\lesssim 3\,\mathrm{Mpc}$].

We can envisage two ways to create the distribution shown in Fig. 8 – through evolution or an uneven distribution of baryonic and non-baryonic material in the early Universe ($z \sim 5$). First, an evolutionary process, which may produce a central concentration of gas surrounded by an 'extended halo' of dark matter, from the infall process which forms the clusters and/or the subsequent infall of subclusters. For example, if a gas-rich cluster fell into a larger cluster the gaseous component would be stripped from it in the dense central regions of the larger cluster, in a manner similar to the ram-pressure stripping of the hot gas from the elliptical galaxy M86 in the Virgo cluster (*e.g.* D. White et al. 1991a), while the collisionless dark matter would pass through unhindered to the other side of the cluster. This process would produce an atmosphere of gas which would be slightly more extended than the virial core of the cluster, due to shock heating, surrounded at larger radius by a halo of dark matter. This dark matter, if bound, may remain at large radius for a relatively large period of time before falling again towards the core of the cluster. Thus, within the framework of hierarchical merging, infalling subclusters may produce significant amount of dark matter at large cluster radii. This scenario requires that clusters are more massive, approaching $10^{16}\,\mathrm{M}_\odot$, than generally considered in current theories of cluster formation, and would result in large peculiar velocities around massive clusters of galaxies. Other methods in which the dark matter could be distributed on larger scales rely on different clustering properties of the dark matter, *e.g.* if the Universe is composed of a mixture of mostly hot with some cold dark matter, or if Λ is non-zero.

Alternatively, if the central concentration of baryons with respect to the dark matter does not occur in the evolutionary scenario, then the gas needs to be distributed differently before the formation of clusters. However, as the gas is more concentrated than the gravitational matter, gravitational effects cannot have been responsible, and the baryons must have been pushed together to form regions of higher density. This could have happened if there was a population of active quasars with strong winds or radiation pressure which produced voids in the early Universe before cluster formation. The baryonic material would have been forced together at the interface between voids, at the sites of cluster formations, while the dark matter would have been less compressed. Clusters would then have inherited the distributions of baryonic and non-baryonic material. This scenario leads to the prediction that there should be a population of objects at the centre of voids.

None of the above solutions for the baryon overdensities resulting from standard primordial nucleosynthesis are very elegant or without problems. Perhaps the most damning fact is that it appears extremely difficult to accumulate enough baryons from a region with a baryon density of at most 6 per cent to provide the overdensity seen to be common in our sample. As there is still evidence for $\Omega_0 = 1$ on large scales, *e.g.* from studies of the structure in clusters (Richstone, Loeb & Turner 1992), and the POTENT analysis of *IRAS* galaxies (Nusser & Dekel 1993, Dekel et al. 1993, Dekel & Rees 1994). We do not appeal to low values of Ω_0, but assume that the dark matter in clusters is spread over a larger radius than the baryons. This means that clusters are several times more massive than is canonically assumed.

5 CONCLUSION

Our deprojection analysis of 19 moderately luminous and distant clusters, observed with the *Einstein Observatory* IPC, shows that cluster baryon fractions are all inconsistent with the mean value for the Universe of $\Omega_\mathrm{b} = 0.05 \pm 0.01 h_{50}^{-2}$, as calculated according to standard, homogeneous, primordial nucleosynthesis (Olive et al. 1990, Walker et al. 1991). The deprojection method produces well-determined gas masses, such that the main uncertainty in the gas mass lies in the value of the Hubble constant, while the overall main uncertainty in the baryon fraction determinations lies is in the gravitational masses. However, this also cannot produce a significant enough effect to reconcile the cluster determinations with the mean value predicted from standard primordial nucleosynthesis. We find, at the 5th and 95th per cent confidence levels, that the baryon fractions of the clusters, in our refined sample of 13, lie between 10 and 22 per cent. *ASCA* should reduce uncertainties in the gas and gravitational mass determinations, by enabling accurate temperature measurements (with adequate spatial resolution) to be made, from which the total masses and baryon fractions of clusters will be accurately determined.

As there is still strong evidence that $\Omega_0 = 1$ on large scales, we have considered the implications that result from conflict between the baryon fractions in clusters and the mean baryon fraction prediction from standard primordial

Figure 8.

This schematic figure shows how the observational results, which indicate baryon fractions approaching 30 per cent, may be reconciled with the mean baryon fraction for the Universe of < 6 per cent ($\Omega_0 = 1$ and $h_{50} = 1$) for the cluster as a whole. The solid lines are the cluster gas and gravitational mass distributions, and the dotted line shows the mass expected within the same volume with a critical density of material and the baryon fraction of 6 per cent ($\Omega_0 = 1$). The reasoning for the more extended nature of the dark matter is given in the main text.

nucleosynthesis. These solutions, which imply clusters are much more massive than generally thought, require halos of dark matter outside the main X-ray extent of the cluster.

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